



Combination of Tevatron Searches for the Standard Model Higgs Boson in the W^+W^- Decay Mode

T. Aaltonen,^{15,*} V. M. Abazov,^{60,†} B. Abbott,^{128,†} M. Abolins,^{113,†} B. S. Acharya,^{35,†} M. Adams,^{91,†} T. Adams,^{87,†}
 J. Adelman,^{90,*} E. Aguilo,^{7,†} G. D. Alexeev,^{60,†} G. Alkhazov,^{64,†} A. Alton,^{111,†,gg} B. Álvarez González,^{68,*y}
 G. Alverson,^{106,†} G. A. Alves,^{2,†} S. Amerio,^{41,40,*} D. Amidei,^{111,*} A. Anastassov,^{93,*} L. S. Ancu,^{59,†} A. Annovi,^{39,*}
 J. Antos,^{65,*} M. Aoki,^{89,†} G. Apollinari,^{89,*} J. Appel,^{89,*} A. Apresyan,^{98,*} T. Arisawa,^{53,*} Y. Arnoud,^{17,†} M. Arov,^{102,†}
 A. Artikov,^{60,*} J. Asaadi,^{135,*} W. Ashmanskas,^{89,*} A. Askew,^{87,†} B. Åsman,^{69,†} O. Atramentov,^{116,†} A. Attal,^{66,*}
 A. Aurisano,^{135,*} C. Avila,^{10,†} F. Azfar,^{77,*} J. BackusMayes,^{140,†} F. Badaud,^{16,†} W. Badgett,^{89,*} L. Bagby,^{89,†} B. Baldin,^{89,†}
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 D. Benjamin,^{125,*} A. Beretvas,^{89,*} S. B. Beri,^{33,†} G. Bernardi,^{20,†} R. Bernhard,^{26,†} I. Bertram,^{72,†} M. Besançon,^{21,†}
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 V. Buescher,^{29,†} V. Bunichev,^{62,†} S. Burdin,^{72,†,hh} K. Burkett,^{89,*} T. H. Burnett,^{140,†} G. Busetto,^{41,40,*} P. Bussey,^{71,*}
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 P. de Barbaro,^{122,*} S. De Cecco,^{46,*} A. Deisher,^{79,*} S. J. de Jong,^{59,†} E. De La Cruz-Burelo,^{57,†} F. Déliot,^{21,†}
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 S. Donati,^{43,42,*} P. Dong,^{89,*} M. D'Onofrio,^{66,*} T. Dorigo,^{40,*} T. Dorland,^{140,†} S. Dube,^{116,*} A. Dubey,^{34,†} L. V. Dudko,^{62,†}
 L. Duflot,^{19,†} D. Duggan,^{116,†} A. Duperrin,^{18,†} S. Dutt,^{33,†} A. Dyshkant,^{92,†} M. Eads,^{115,†} K. Ebina,^{53,*} D. Edmunds,^{113,†}
 A. Elagin,^{135,*} J. Ellison,^{83,†} V. D. Elvira,^{89,†} Y. Enari,^{20,†} S. Eno,^{104,†} R. Erbacher,^{80,*} D. Errede,^{94,*} S. Errede,^{94,*}
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 J. P. Fernandez,^{67,*} C. Ferrazza,^{45,42,*} F. Fiedler,^{29,†} R. Field,^{86,*} F. Filthaut,^{59,†} W. Fisher,^{113,†} H. E. Fisk,^{89,†}
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 J. E. Garcia,^{70,*} A. Garcia-Bellido,^{122,†} A. F. Garfinkel,^{98,*} P. Garosi,^{44,42,*} V. Gavrilov,^{61,†} P. Gay,^{16,†} W. Geist,^{22,†}
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 C. M. Ginsburg,^{89,*} G. Ginther,^{89,122,†} N. Giokaris,^{32,*} M. Giordani,^{49,48,*} P. Giromini,^{39,*} M. Giunta,^{42,*} G. Giurgiu,^{103,*}

- V. Glagolev,^{60,*} D. Glenzinski,^{89,*} M. Gold,^{118,*} N. Goldschmidt,^{86,*} A. Golossanov,^{89,*} G. Golovanov,^{60,†} B. Gómez,^{10,†} G. Gomez,^{68,*} G. Gomez-Ceballos,^{108,*} M. Goncharov,^{108,*} O. González,^{67,*} I. Gorelov,^{118,*} A. T. Goshaw,^{125,*} K. Goulianos,^{121,*} A. Goussiou,^{140,†} P. D. Grannis,^{123,†} S. Greder,^{22,†} H. Greenlee,^{89,†} Z. D. Greenwood,^{102,†} E. M. Gregores,^{4,†} G. Grenier,^{23,†} A. Gresele,^{41,40,*} S. Grinstein,^{66,*} Ph. Gris,^{16,†} J.-F. Grivaz,^{19,†} A. Grohsjean,^{21,†} C. Grosso-Pilcher,^{90,*} R. C. Group,^{89,*} U. Grundler,^{94,*} S. Grünendahl,^{89,†} M. W. Grünwald,^{36,†} J. Guimaraes da Costa,^{107,*} Z. Gunay-Unalan,^{113,*} F. Guo,^{123,†} J. Guo,^{123,†} G. Gutierrez,^{89,†} P. Gutierrez,^{128,†} A. Haas,^{120,†,ii} C. Haber,^{79,*} P. Haefner,^{30,†} S. Hagopian,^{87,†} S. R. Hahn,^{89,*} J. Haley,^{106,†} E. Halkiadakis,^{116,*} I. Hall,^{113,†} B.-Y. Han,^{122,*} J. Y. Han,^{122,*} L. Han,^{8,†} F. Happacher,^{39,*} K. Hara,^{52,*} K. Harder,^{76,†} D. Hare,^{116,*} M. Hare,^{109,*} A. Harel,^{122,†} R. F. Harr,^{112,*} M. Hartz,^{132,*} K. Hatakeyama,^{138,*} J. M. Hauptman,^{99,†} C. Hays,^{77,*} J. Hays,^{74,†} T. Hebbeker,^{24,†} M. Heck,^{28,*} D. Hedin,^{92,†} J. G. Hegeman,^{58,†} J. Heinrich,^{130,*} A. P. Heinson,^{83,†} U. Heintz,^{133,†} C. Hensel,^{27,†} I. Heredia-De La Cruz,^{57,†} M. Herndon,^{141,*} K. Herner,^{111,†} G. Hesketh,^{106,†} J. Heuser,^{28,*} S. Hewamanage,^{138,*} D. Hidas,^{116,*} M. D. Hildreth,^{97,†} C. S. Hill,^{84,*d} R. Hirosky,^{139,†} D. Hirschbuehl,^{28,*} T. Hoang,^{87,†} J. D. Hobbs,^{123,†} A. Hocker,^{89,*} B. Hoeneisen,^{14,†} M. Hohlfeld,^{29,†} S. Hossain,^{128,†} P. Houben,^{58,†} S. Hou,^{9,*} M. Houlden,^{73,*} S.-C. Hsu,^{79,*} Y. Hu,^{123,†} Z. Hubacek,^{12,†} R. E. Hughes,^{126,*} M. Hurwitz,^{90,*} U. Husemann,^{85,*} N. Huske,^{20,†} M. Hussein,^{113,*} J. Huston,^{113,*} V. Hynek,^{12,†} I. Iashvili,^{119,†} R. Illingworth,^{89,†} J. Incandela,^{84,*} G. Introzzi,^{42,*} M. Iori,^{47,46,*} A. S. Ito,^{89,†} A. Ivanov,^{80,*r} S. Jabeen,^{105,†} M. Jaffré,^{19,†} S. Jain,^{119,†} E. James,^{89,*} D. Jamin,^{18,†} D. Jang,^{131,*} B. Jayatilaka,^{125,*} E. J. Jeon,^{54,*} R. Jesik,^{74,†} M. K. Jha,^{37,*} S. Jindariani,^{89,*} K. Johns,^{78,†} C. Johnson,^{120,†} M. Johnson,^{89,†} W. Johnson,^{80,*} D. Johnston,^{115,†} A. Jonckheere,^{89,†} M. Jones,^{98,*} P. Jonsson,^{74,†} K. K. Joo,^{54,*} S. Y. Jun,^{131,*} J. E. Jung,^{54,*} T. R. Junk,^{89,*} A. Juste,^{89,†,jj} E. Kajfasz,^{18,†} T. Kamon,^{135,*} P. E. Karchin,^{112,*} D. Kar,^{86,*} D. Karmanov,^{62,†} P. A. Kasper,^{89,†} Y. Kato,^{51,*n} I. Katsanos,^{115,†} V. Kaushik,^{134,†} R. Kehoe,^{136,†} R. Kephart,^{89,*} S. Kermiche,^{18,†} W. Ketchum,^{90,*} J. Keung,^{130,*} N. Khalatyan,^{89,†} A. Khanov,^{129,†} A. Kharchilava,^{119,†} Y. N. Kharzhev,^{60,†} D. Khatidze,^{133,†} V. Khotilovich,^{135,*} B. Kilminster,^{89,*} D. H. Kim,^{54,*} H. S. Kim,^{54,*} H. W. Kim,^{54,*} J. E. Kim,^{54,*} M. J. Kim,^{39,*} S. B. Kim,^{54,*} S. H. Kim,^{52,*} Y. K. Kim,^{90,*} N. Kimura,^{53,*} M. H. Kirby,^{93,†} L. Kirsch,^{110,*} M. Kirsch,^{24,†} S. Klimenko,^{86,*} J. M. Kohli,^{33,†} K. Kondo,^{53,*} D. J. Kong,^{54,*} J. Konigsberg,^{86,*} A. Korytov,^{86,*} A. V. Kotwal,^{125,*} A. V. Kozelov,^{63,†} J. Kraus,^{113,†} M. Kreps,^{28,*} J. Kroll,^{130,*} D. Krop,^{90,*} N. Krumnack,^{138,*q} M. Kruse,^{125,*} V. Krutelyov,^{84,*} T. Kuhr,^{28,*} N. P. Kulkarni,^{112,*} A. Kumar,^{119,†} A. Kupco,^{13,†} M. Kurata,^{52,*} T. Kurča,^{23,†} V. A. Kuzmin,^{62,†} J. Kvita,^{11,†} S. Kwang,^{90,*} A. T. Laasanen,^{98,*} D. Lam,^{97,†} S. Lami,^{42,*} S. Lammel,^{89,*} S. Lammers,^{95,†} M. Lancaster,^{75,*} R. L. Lander,^{80,*} G. Landsberg,^{133,†} K. Lannon,^{126,*w} A. Lath,^{116,*} G. Latino,^{44,42,*} I. Lazzizzera,^{41,40,*} P. Lebrun,^{23,†} T. LeCompte,^{88,*} E. Lee,^{135,*} H. S. Lee,^{90,*} H. S. Lee,^{55,†} J. S. Lee,^{54,*} S. W. Lee,^{135,*z} W. M. Lee,^{89,†} A. Leflat,^{62,†} J. Lellouch,^{20,†} S. Leone,^{42,*} J. D. Lewis,^{89,*} L. Li,^{83,†} Q. Z. Li,^{89,†} S. M. Lietti,^{5,†} J. K. Lim,^{55,†} J. Linacre,^{77,*} D. Lincoln,^{89,†} C.-J. Lin,^{79,*} M. Lindgren,^{89,*} J. Linnemann,^{113,†} V. V. Lipaev,^{63,†} E. Lipeles,^{130,*} R. Lipton,^{89,†} A. Lister,^{70,*} D. O. Litvintsev,^{89,*} C. Liu,^{132,*} T. Liu,^{89,*} Y. Liu,^{8,†} Z. Liu,^{7,†} A. Lobodenko,^{64,†} N. S. Lockyer,^{130,*} A. Loginov,^{85,*} M. Lokajicek,^{13,†} L. Lovas,^{65,*} P. Love,^{72,†} H. J. Lubatti,^{140,†} D. Lucchesi,^{41,40,*} J. Lueck,^{28,*} P. Lujan,^{79,*} P. Lukens,^{89,*} R. Luna-Garcia,^{57,†,kk} G. Lungu,^{121,*} A. L. Lyon,^{89,†} R. Lysak,^{65,*} J. Lys,^{79,*} A. K. A. Maciel,^{2,†} D. Mackin,^{137,†} D. MacQueen,^{6,*} R. Madrak,^{89,*} K. Maeshima,^{89,*} R. Magaña-Villalba,^{57,†} K. Makhoul,^{108,*} P. Maksimovic,^{103,*} P. K. Mal,^{78,†} S. Malde,^{77,*} S. Malik,^{75,*} S. Malik,^{115,†} V. L. Malyshev,^{60,†} G. Manca,^{73,*f} A. Manousakis-Katsikakis,^{32,*} Y. Maravin,^{101,†} F. Margaroli,^{98,*} C. Marino,^{28,*} C. P. Marino,^{94,*} A. Martin,^{85,*} V. Martin,^{71,*l} M. Martínez,^{66,*} R. Martínez-Ballarín,^{67,*} J. Martínez-Ortega,^{57,†} P. Mastrandrea,^{46,*} M. Mathis,^{103,*} P. Mättig,^{31,†} M. E. Mattson,^{112,*} P. Mazzanti,^{37,*} R. McCarthy,^{123,†} K. S. McFarland,^{122,*} C. L. McGivern,^{100,†} P. McIntyre,^{135,*} R. McNulty,^{73,*k} A. Mehta,^{73,*} P. Mehtala,^{15,*} M. M. Meijer,^{59,†} A. Melnitchouk,^{114,†} L. Mendoza,^{10,†} D. Menezes,^{92,†} A. Menzione,^{42,*} P. G. Mercadante,^{4,†} M. Merkin,^{62,†} C. Mesropian,^{121,*} A. Meyer,^{24,†} J. Meyer,^{27,†} T. Miao,^{89,*} D. Mietlicki,^{111,*} N. Miladinovic,^{110,*} R. Miller,^{113,*} C. Mills,^{107,*} M. Milnik,^{28,*} A. Mitra,^{9,*} G. Mitselmakher,^{86,*} H. Miyake,^{52,*} S. Moed,^{107,*} N. Moggi,^{37,*} N. K. Mondal,^{35,†} M. N. Mondragon,^{89,*o} C. S. Moon,^{54,*} R. Moore,^{89,*} M. J. Morello,^{42,*} J. Morlock,^{28,*} T. Moulik,^{100,†} P. Movilla Fernandez,^{89,*} G. S. Muanza,^{18,†} A. Mukherjee,^{89,*} M. Mulhearn,^{139,†} Th. Muller,^{28,*} J. Mülmenstädt,^{79,*} O. Mundal,^{25,†} L. Mundim,^{3,†} P. Murat,^{89,*} M. Mussini,^{38,37,*} J. Nachtman,^{89,*p} Y. Nagai,^{52,*} J. Naganoma,^{52,*} E. Nagy,^{18,†} M. Naimuddin,^{34,†} K. Nakamura,^{52,*} I. Nakano,^{50,*} A. Napier,^{109,*} M. Narain,^{133,†} R. Nayyar,^{34,†} H. A. Neal,^{111,†} J. P. Negret,^{10,†} J. Nett,^{141,*} C. Neu,^{130,*cc} M. S. Neubauer,^{94,*} S. Neubauer,^{28,*} P. Neustroev,^{64,†} J. Nielsen,^{79,*h} H. Nilsen,^{26,†} L. Nodulman,^{88,*} H. Nogima,^{3,†} M. Norman,^{81,*} O. Norniella,^{94,*} S. F. Novaes,^{5,†} T. Nunnemann,^{30,†} E. Nurse,^{75,*} L. Oakes,^{77,*} G. Obrant,^{64,†} S. H. Oh,^{125,*} Y. D. Oh,^{54,*} I. Oksuzian,^{86,*} T. Okusawa,^{51,*} D. Onoprienko,^{101,†} R. Orava,^{15,*} J. Orduna,^{57,†} N. Osman,^{74,†} J. Osta,^{97,†} K. Osterberg,^{15,*} R. Otec,^{12,†} G. J. Otero y Garzón,^{1,†} M. Owen,^{76,†} M. Padilla,^{83,†} P. Padley,^{137,†}

- S. Pagan Griso,^{41,40,*} C. Pagliarone,^{48,*} E. Palencia,^{89,*} M. Pangilinan,^{133,†} V. Papadimitriou,^{89,*} A. Papaikonomou,^{28,*} A. A. Paramanov,^{88,*} N. Parashar,^{96,†} V. Parihar,^{133,†} S.-J. Park,^{27,†} S. K. Park,^{55,†} B. Parks,^{126,*} J. Parsons,^{120,†} R. Partridge,^{133,†} N. Parua,^{95,†} S. Pashapour,^{6,*} J. Patrick,^{89,*} A. Patwa,^{124,†} G. Pauletta,^{49,48,*} M. Paulini,^{131,*} C. Paus,^{108,*} T. Peiffer,^{28,*} D. E. Pellett,^{80,*} B. Penning,^{89,†} A. Penzo,^{48,*} M. Perfilov,^{62,†} K. Peters,^{76,†} Y. Peters,^{76,†} P. Pétroff,^{19,†} T. J. Phillips,^{125,*} G. Piacentino,^{42,*} E. Pianori,^{130,*} R. Piegaia,^{1,†} L. Pinera,^{86,*} J. Piper,^{113,†} K. Pitts,^{94,*} C. Plager,^{82,*} M.-A. Pleier,^{124,†} P. L. M. Podesta-Lerma,^{57,†,ll} V. M. Podstavkov,^{89,†} M.-E. Pol,^{2,†} P. Polozov,^{61,†} L. Pondrom,^{141,*} A. V. Popov,^{63,†} K. Potamianos,^{98,*} O. Poukhov,^{60,*a} M. Prewitt,^{137,†} D. Price,^{95,†} F. Prokoshin,^{60,*bb} A. Pronko,^{89,*} S. Protopopescu,^{124,†} F. Ptohos,^{89,*j} E. Pueschel,^{131,*} G. Punzi,^{43,42,*} J. Pursley,^{141,*} J. Qian,^{111,†} A. Quadt,^{27,†} B. Quinn,^{114,†} J. Rademacker,^{77,*d} A. Rahaman,^{132,*} V. Ramakrishnan,^{141,*} M. S. Rangel,^{19,†} K. Ranjan,^{34,†} N. Ranjan,^{98,*} P. N. Ratoff,^{72,†} I. Razumov,^{63,†} I. Redondo,^{67,*} P. Renkel,^{136,†} P. Renton,^{77,*} M. Renz,^{28,*} M. Rescigno,^{46,*} P. Rich,^{76,†} S. Richter,^{28,*} M. Rijssenbeek,^{123,†} F. Rimondi,^{38,37,*} I. Ripp-Baudot,^{22,†} L. Ristori,^{42,*} F. Rizatdinova,^{129,†} S. Robinson,^{74,†} A. Robson,^{71,*} T. Rodrigo,^{68,*} T. Rodriguez,^{130,*} E. Rogers,^{94,*} S. Rolli,^{109,*} M. Rominsky,^{128,†} R. Roser,^{89,*} M. Rossi,^{48,*} R. Rossin,^{84,*} P. Roy,^{6,*} C. Royon,^{21,†} P. Rubinov,^{89,†} R. Ruchti,^{97,†} A. Ruiz,^{68,*} J. Russ,^{131,*} V. Rusu,^{89,*} B. Rutherford,^{89,*} H. Saarikko,^{15,*} A. Safonov,^{135,*} G. Safronov,^{61,†} G. Sajot,^{17,†} W. K. Sakumoto,^{122,*} A. Sánchez-Hernández,^{57,†} M. P. Sanders,^{30,†} B. Sanghi,^{89,†} L. Santi,^{49,48,*} L. Sartori,^{42,*} K. Sato,^{52,*} G. Savage,^{89,†} V. Saveliev,^{20,*x} A. Savoy-Navarro,^{20,*} L. Sawyer,^{102,†} T. Scanlon,^{74,†} D. Schaile,^{30,†} R. D. Schamberger,^{123,†} Y. Scheglov,^{64,†} H. Schellman,^{93,†} P. Schlabach,^{89,*} T. Schliephake,^{31,†} S. Schlobohm,^{140,†} A. Schmidt,^{28,*} E. E. Schmidt,^{89,*} M. A. Schmidt,^{90,*} M. P. Schmidt,^{85,*a} M. Schmitt,^{93,*} C. Schwanenberger,^{76,†} T. Schwarz,^{80,*} R. Schwienhorst,^{113,†} L. Scodellaro,^{68,*} A. Scribano,^{44,42,*} F. Scuri,^{42,*} A. Sedov,^{98,*} S. Seidel,^{118,*} Y. Seiya,^{51,*} J. Sekaric,^{100,†} A. Semenov,^{60,*} H. Severini,^{128,†} L. Sexton-Kennedy,^{89,*} F. Sforza,^{43,42,*} A. Sfyrly,^{94,*} E. Shabalina,^{27,†} S. Z. Shalhout,^{112,*} V. Shary,^{21,†} A. A. Shchukin,^{63,†} T. Shears,^{73,*} P. F. Shepard,^{132,*} M. Shimojima,^{52,*v} S. Shiraishi,^{90,*} R. K. Shivpuri,^{34,†} M. Shochet,^{90,*} Y. Shon,^{141,*} I. Shreyber,^{61,*} V. Simak,^{12,†} A. Simonenko,^{60,*} P. Sinervo,^{6,*} V. Sirotenko,^{89,†} A. Sisakyan,^{60,*} P. Skubic,^{128,†} P. Slattery,^{122,†} A. J. Slaughter,^{89,*} J. Slaunwhite,^{126,*} K. Sliwa,^{109,*} D. Smirnov,^{97,†} J. R. Smith,^{80,*} F. D. Snider,^{89,*} R. Snihur,^{6,*} G. R. Snow,^{115,†} J. Snow,^{127,†} S. Snyder,^{124,†} A. Soha,^{89,*} S. Söldner-Rembold,^{76,†} S. Somalwar,^{116,*} L. Sonnenschein,^{24,†} A. Sopczak,^{72,†} V. Sorin,^{66,*} M. Sosebee,^{134,†} K. Soustruznik,^{11,†} B. Spurlock,^{134,†} P. Squillacioti,^{44,42,*} M. Stanitzki,^{85,*} J. Stark,^{17,†} R. St. Denis,^{71,*} B. Stelzer,^{6,*} O. Stelzer-Chilton,^{6,*} D. Stentz,^{93,*} V. Stolin,^{61,†} D. A. Stoyanova,^{63,†} J. Strandberg,^{111,†} M. A. Strang,^{119,†} E. Strauss,^{123,†} M. Strauss,^{128,†} R. Ströhmer,^{30,†} J. Strologas,^{118,*} D. Strom,^{91,†} G. L. Strycker,^{111,*} L. Stutte,^{89,†} J. S. Suh,^{54,*} A. Sukhanov,^{86,*} I. Suslov,^{60,*} P. Svoisky,^{59,†} A. Taffard,^{94,*g} M. Takahashi,^{76,†} R. Takashima,^{50,*} Y. Takeuchi,^{52,*} R. Tanaka,^{50,*} A. Tanasijczuk,^{1,†} J. Tang,^{90,*} W. Taylor,^{7,†} M. Tecchio,^{111,*} P. K. Teng,^{9,*} J. Thom,^{89,*i} J. Thome,^{131,*} G. A. Thompson,^{94,*} E. Thomson,^{130,*} B. Tiller,^{30,†} P. Tipton,^{85,*} M. Titov,^{21,†} S. Tkaczyk,^{89,*} D. Toback,^{135,*} S. Tokar,^{65,*} V. V. Tokmenin,^{60,†} K. Tollefson,^{113,*} T. Tomura,^{52,*} D. Tonelli,^{89,*} S. Torre,^{39,*} D. Torretta,^{89,*} P. Totaro,^{49,48,*} M. Trovato,^{45,42,*} S.-Y. Tsai,^{9,*} D. Tsybychev,^{123,†} P. Tito-Guzmán,^{67,*} B. Tuchming,^{21,†} Y. Tu,^{130,*} C. Tully,^{117,†} N. Turini,^{44,42,*} P. M. Tuts,^{120,†} F. Ukegawa,^{52,*} R. Unalan,^{113,†} S. Uozumi,^{54,*} L. Uvarov,^{64,†} S. Uvarov,^{64,†} S. Uzunyan,^{92,†} P. J. van den Berg,^{58,†} R. Van Kooten,^{95,†} W. M. van Leeuwen,^{58,†} N. van Remortel,^{15,*c} N. Varelas,^{91,†} A. Varganov,^{111,*} E. W. Varnes,^{78,†} I. A. Vasilyev,^{63,†} E. Vataga,^{45,42,*} F. Vázquez,^{86,*o} G. Velev,^{89,*} C. Vellidis,^{32,*} P. Verdier,^{23,†} L. S. Vertogradov,^{60,†} M. Verzocchi,^{89,†} M. Vesterinen,^{76,†} M. Vidal,^{67,*} I. Vila,^{68,*} D. Vilanova,^{21,†} R. Vilar,^{68,*} P. Vint,^{74,†} M. Vogel,^{118,*} P. Vokac,^{12,†} I. Volobouev,^{79,*z} G. Volpi,^{43,42,*} P. Wagner,^{130,*} R. G. Wagner,^{88,*} R. L. Wagner,^{89,*} W. Wagner,^{28,*dd} J. Wagner-Kuhr,^{28,*} H. D. Wahl,^{87,†} T. Wakisaka,^{51,*} R. Wallny,^{82,*} M. H. L. S. Wang,^{122,†} S. M. Wang,^{9,*} A. Warburton,^{6,*} J. Warchol,^{97,†} D. Waters,^{75,*} G. Watts,^{140,†} M. Wayne,^{97,†} G. Weber,^{29,†} M. Weber,^{89,†,mm} M. Weinberger,^{135,*} J. Weinelt,^{28,*} W. C. Wester III,^{89,*} M. Wetstein,^{104,†} A. White,^{134,†} B. Whitehouse,^{109,*} D. Whiteson,^{130,*g} D. Wicke,^{29,†} A. B. Wicklund,^{88,*} E. Wicklund,^{89,*} S. Wilbur,^{90,*} G. Williams,^{6,*} H. H. Williams,^{130,*} M. R. J. Williams,^{72,†} G. W. Wilson,^{100,†} P. Wilson,^{89,*} S. J. Wimpenny,^{83,†} B. L. Winer,^{126,*} P. Wittich,^{89,*i} M. Wobisch,^{102,†} S. Wolbers,^{89,*} C. Wolfe,^{90,*} H. Wolfe,^{126,*} D. R. Wood,^{106,†} T. Wright,^{111,*} X. Wu,^{70,*} F. Würthwein,^{81,*} T. R. Wyatt,^{76,†} Y. Xie,^{89,†} C. Xu,^{111,†} S. Yacoub,^{93,†} A. Yagil,^{81,*} R. Yamada,^{89,†} K. Yamamoto,^{51,*} J. Yamaoka,^{125,*} U. K. Yang,^{90,*t} W.-C. Yang,^{76,†} Y. C. Yang,^{54,*} W. M. Yao,^{79,*} T. Yasuda,^{89,†} Y. A. Yatsunenko,^{60,†} Z. Ye,^{89,†} G. P. Yeh,^{89,*} K. Yi,^{89,*p} H. Yin,^{8,†} K. Yip,^{124,†} J. Yoh,^{89,*} H. D. Yoo,^{133,†} K. Yorita,^{53,*} T. Yoshida,^{51,*m} S. W. Youn,^{89,†} G. B. Yu,^{125,*} I. Yu,^{54,*} J. Yu,^{134,†} S. S. Yu,^{89,*} J. C. Yun,^{89,*} A. Zanetti,^{48,*} C. Zeitnitz,^{31,†} S. Zelitch,^{139,†} Y. Zeng,^{125,*} X. Zhang,^{94,*} T. Zhao,^{140,†} Y. Zheng,^{82,*e} B. Zhou,^{111,†} J. Zhu,^{123,†} M. Zielinski,^{122,†} D. Zieminska,^{95,†} L. Zivkovic,^{120,†} S. Zucchelli,^{38,37,*} V. Zutshi,^{92,†} and E. G. Zverev^{62,†}

(*CDF Collaboration)

(†D0 Collaboration)

- ¹Universidad de Buenos Aires, Buenos Aires, Argentina
- ²LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
- ³Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
- ⁴Universidade Federal do ABC, Santo André, Brazil
- ⁵Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil
- ⁶Institute of Particle Physics: McGill University, Montréal, Québec, Canada;
Simon Fraser University, Burnaby, British Columbia, Canada;
University of Toronto, Toronto, Ontario, Canada;
and TRIUMF, Vancouver, British Columbia, Canada
- ⁷Simon Fraser University, Burnaby, British Columbia, Canada; and York University, Toronto, Ontario, Canada
- ⁸University of Science and Technology of China, Hefei, People's Republic of China
- ⁹Institute of Physics, Academia Sinica, Taipei, Taiwan, Republic of China
- ¹⁰Universidad de los Andes, Bogotá, Colombia
- ¹¹Center for Particle Physics, Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
- ¹²Czech Technical University in Prague, Prague, Czech Republic
- ¹³Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
- ¹⁴Universidad San Francisco de Quito, Quito, Ecuador
- ¹⁵Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics,
FIN-00014, Helsinki, Finland
- ¹⁶LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
- ¹⁷LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France
- ¹⁸CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
- ¹⁹LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
- ²⁰LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France
- ²¹CEA, Irfu, SPP, Saclay, France
- ²²IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
- ²³IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France
- ²⁴III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
- ²⁵Physikalisches Institut, Universität Bonn, Bonn, Germany
- ²⁶Physikalisches Institut, Universität Freiburg, Freiburg, Germany
- ²⁷II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
- ²⁸Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology, Karlsruhe, Germany
- ²⁹Institut für Physik, Universität Mainz, Mainz, Germany
- ³⁰Ludwig-Maximilians-Universität München, München, Germany
- ³¹Fachbereich Physik, University of Wuppertal, Wuppertal, Germany
- ³²University of Athens, 157 01 Athens, Greece
- ³³Panjab University, Chandigarh, India
- ³⁴Delhi University, Delhi, India
- ³⁵Tata Institute of Fundamental Research, Mumbai, India
- ³⁶University College Dublin, Dublin, Ireland
- ³⁷Istituto Nazionale di Fisica Nucleare Bologna, I-40127 Bologna, Italy
- ³⁸University of Bologna, I-40127 Bologna, Italy
- ³⁹Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy
- ⁴⁰Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, I-35131 Padova, Italy
- ⁴¹University of Padova, I-35131 Padova, Italy
- ⁴²Istituto Nazionale di Fisica Nucleare Pisa, I-56127 Pisa, Italy
- ⁴³University of Pisa, I-56127 Pisa, Italy
- ⁴⁴University of Siena, I-56127 Pisa, Italy
- ⁴⁵Scuola Normale Superiore, I-56127 Pisa, Italy
- ⁴⁶Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, I-00185 Roma, Italy
- ⁴⁷Sapienza Università di Roma, I-00185 Roma, Italy
- ⁴⁸Istituto Nazionale di Fisica Nucleare Trieste/Udine, I-34100 Trieste, I-33100 Udine, Italy
- ⁴⁹University of Trieste/Udine, I-33100 Udine, Italy
- ⁵⁰Okayama University, Okayama 700-8530, Japan
- ⁵¹Osaka City University, Osaka 588, Japan
- ⁵²University of Tsukuba, Tsukuba, Ibaraki 305, Japan

- ⁵³Waseda University, Tokyo 169, Japan
- ⁵⁴Center for High Energy Physics: Kyungpook National University, Daegu, Korea;
Seoul National University, Seoul, Korea;
Sungkyunkwan University, Suwon, Korea;
Korea Institute of Science and Technology Information, Daejeon, Korea;
Chonnam National University, Gwangju, Korea; Chonbuk National University, Jeonju, Korea
- ⁵⁵Korea Detector Laboratory, Korea University, Seoul, Korea
- ⁵⁶SungKyunKwan University, Suwon, Korea
- ⁵⁷CINVESTAV, Mexico City, Mexico
- ⁵⁸FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands
- ⁵⁹Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands
- ⁶⁰Joint Institute for Nuclear Research, Dubna, Russia
- ⁶¹Institution for Theoretical and Experimental Physics, Moscow, Russia
- ⁶²Moscow State University, Moscow, Russia
- ⁶³Institute for High Energy Physics, Protvino, Russia
- ⁶⁴Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- ⁶⁵Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia
- ⁶⁶Institut de Fisica d'Altes Energies, Universitat Autònoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain
- ⁶⁷Centro de Investigaciones Energeticas Medioambientales y Tecnológicas, E-28040 Madrid, Spain
- ⁶⁸Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain
- ⁶⁹Stockholm University, Stockholm, Sweden, and Uppsala University, Uppsala, Sweden
- ⁷⁰University of Geneva, CH-1211 Geneva 4, Switzerland
- ⁷¹Glasgow University, Glasgow G12 8QQ, United Kingdom
- ⁷²Lancaster University, Lancaster LA1 4YB, United Kingdom
- ⁷³University of Liverpool, Liverpool L69 7ZE, United Kingdom
- ⁷⁴Imperial College London, London SW7 2AZ, United Kingdom
- ⁷⁵University College London, London WC1E 6BT, United Kingdom
- ⁷⁶The University of Manchester, Manchester M13 9PL, United Kingdom
- ⁷⁷University of Oxford, Oxford OX1 3RH, United Kingdom
- ⁷⁸University of Arizona, Tucson, Arizona 85721, USA
- ⁷⁹Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
- ⁸⁰University of California, Davis, Davis, California 95616, USA
- ⁸¹University of California, San Diego, La Jolla, California 92093, USA
- ⁸²University of California, Los Angeles, Los Angeles, California 90024, USA
- ⁸³University of California, Riverside, Riverside, California 92521, USA
- ⁸⁴University of California, Santa Barbara, Santa Barbara, California 93106, USA
- ⁸⁵Yale University, New Haven, Connecticut 06520, USA
- ⁸⁶University of Florida, Gainesville, Florida 32611, USA
- ⁸⁷Florida State University, Tallahassee, Florida 32306, USA
- ⁸⁸Argonne National Laboratory, Argonne, Illinois 60439, USA
- ⁸⁹Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
- ⁹⁰Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA
- ⁹¹University of Illinois at Chicago, Chicago, Illinois 60607, USA
- ⁹²Northern Illinois University, DeKalb, Illinois 60115, USA
- ⁹³Northwestern University, Evanston, Illinois 60208, USA
- ⁹⁴University of Illinois, Urbana, Illinois 61801, USA
- ⁹⁵Indiana University, Bloomington, Indiana 47405, USA
- ⁹⁶Purdue University Calumet, Hammond, Indiana 46323, USA
- ⁹⁷University of Notre Dame, Notre Dame, Indiana 46556, USA
- ⁹⁸Purdue University, West Lafayette, Indiana 47907, USA
- ⁹⁹Iowa State University, Ames, Iowa 50011, USA
- ¹⁰⁰University of Kansas, Lawrence, Kansas 66045, USA
- ¹⁰¹Kansas State University, Manhattan, Kansas 66506, USA
- ¹⁰²Louisiana Tech University, Ruston, Louisiana 71272, USA
- ¹⁰³The Johns Hopkins University, Baltimore, Maryland 21218, USA
- ¹⁰⁴University of Maryland, College Park, Maryland 20742, USA
- ¹⁰⁵Boston University, Boston, Massachusetts 02215, USA
- ¹⁰⁶Northeastern University, Boston, Massachusetts 02115, USA
- ¹⁰⁷Harvard University, Cambridge, Massachusetts 02138, USA
- ¹⁰⁸Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
- ¹⁰⁹Tufts University, Medford, Massachusetts 02155, USA

- ¹¹⁰Brandeis University, Waltham, Massachusetts 02254, USA
¹¹¹University of Michigan, Ann Arbor, Michigan 48109, USA
¹¹²Wayne State University, Detroit, Michigan 48201, USA
¹¹³Michigan State University, East Lansing, Michigan 48824, USA
¹¹⁴University of Mississippi, University, Mississippi 38677, USA
¹¹⁵University of Nebraska, Lincoln, Nebraska 68588, USA
¹¹⁶Rutgers University, Piscataway, New Jersey 08855, USA
¹¹⁷Princeton University, Princeton, New Jersey 08544, USA
¹¹⁸University of New Mexico, Albuquerque, New Mexico 87131, USA
¹¹⁹State University of New York, Buffalo, New York 14260, USA
¹²⁰Columbia University, New York, New York 10027, USA
¹²¹The Rockefeller University, New York, New York 10021, USA
¹²²University of Rochester, Rochester, New York 14627, USA
¹²³State University of New York, Stony Brook, New York 11794, USA
¹²⁴Brookhaven National Laboratory, Upton, New York 11973, USA
¹²⁵Duke University, Durham, North Carolina 27708, USA
¹²⁶The Ohio State University, Columbus, Ohio 43210, USA
¹²⁷Langston University, Langston, Oklahoma 73050, USA
¹²⁸University of Oklahoma, Norman, Oklahoma 73019, USA
¹²⁹Oklahoma State University, Stillwater, Oklahoma 74078, USA
¹³⁰University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
¹³¹Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA
¹³²University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
¹³³Brown University, Providence, Rhode Island 02912, USA
¹³⁴University of Texas, Arlington, Texas 76019, USA
¹³⁵Texas A&M University, College Station, Texas 77843, USA
¹³⁶Southern Methodist University, Dallas, Texas 75275, USA
¹³⁷Rice University, Houston, Texas 77005, USA
¹³⁸Baylor University, Waco, Texas 76798, USA
¹³⁹University of Virginia, Charlottesville, Virginia 22901, USA
¹⁴⁰University of Washington, Seattle, Washington 98195, USA
¹⁴¹University of Wisconsin, Madison, Wisconsin 53706, USA
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We combine searches by the CDF and D0 Collaborations for a Higgs boson decaying to W^+W^- . The data correspond to an integrated total luminosity of 4.8 (CDF) and 5.4 (D0) fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron collider. No excess is observed above background expectation, and resulting limits on Higgs boson production exclude a standard model Higgs boson in the mass range 162–166 GeV at the 95% C.L.

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Finding the last unobserved fundamental particle in the standard model (SM), the Higgs boson, is a major goal of particle physics, and the search for its existence is a central component of Fermilab's Tevatron program. Direct searches at the CERN LEP collider have set a limit on the Higgs boson mass of $m_H > 114.4$ GeV at the 95% C.L. [1]. Combining this limit with precision electroweak measurements constrains the mass of the SM Higgs boson to be less than 186 GeV at the 95% C.L. [2]. The favored mass range therefore places the SM Higgs boson within the reach of the experiments at the Fermilab Tevatron collider.

In this Letter, we combine searches for Higgs bosons (H) decaying to W^+W^- performed by the CDF and D0 Collaborations [3,4]. These searches are particularly sensitive to a Higgs boson with mass $130 < m_H < 200$ GeV. The data analyzed correspond to integrated luminosities of 4.8 fb^{-1} and 5.4 fb^{-1} collected with the CDF and D0

detectors, respectively. We use all significant production modes, namely, gluon-gluon fusion ($gg \rightarrow H$), associated production ($q\bar{q} \rightarrow WH$ or ZH), and vector boson fusion ($q\bar{q} \rightarrow q\bar{q}H$, where the quarks radiate weak gauge bosons that fuse to form the H , and is referred to as VBF).

The event selections used in the CDF and D0 analyses are similar. Both collaborations select events with large missing transverse energy and two oppositely charged, isolated leptons, targeting the $H \rightarrow W^+W^-$ signal in which both W bosons decay leptonically. The D0 selection classifies events in three channels, e^+e^- , $e^\pm\mu^\mp$, and $\mu^+\mu^-$. The CDF selection separates opposite-sign dilepton candidate events into five nonoverlapping channels, classifying events by their jet multiplicity (0, 1, or ≥ 2); the 0- and 1-jet channels are further divided depending on whether one or both leptons are in the central part of the detector. In addition, CDF searches for Higgs boson events

containing same-sign lepton pairs, mainly produced in WH and ZH associated production.

The presence of neutrinos in the final state prevents full reconstruction of the Higgs boson mass. Other variables are used to search for a signal in the presence of appreciable background. For example, the azimuthal angle between the leptons in signal events is smaller on average than that in background events due to the scalar nature of the Higgs boson and the parity violation in W^\pm decays. The missing transverse energy is larger, and the total transverse energy of the jets is smaller, in signal events than in background events. The final discriminants are binned neural-network outputs based on several kinematic input variables [3,4]. A dedicated network is trained for each Higgs boson mass tested. For CDF, the inputs include likelihoods constructed from matrix-element probabilities. Compared with earlier Tevatron $H \rightarrow W^+W^-$ analyses, the new analyses use larger data samples, include all significant signal production mechanisms, and have undergone additional improvements in search sensitivity.

The Higgs boson signals are simulated with PYTHIA [5], using CTEQ5L [6] (CDF) and CTEQ6L1 [7] (D0) parton distribution functions (PDF) at leading order (LO). We normalize our predictions for the Higgs boson signals to the most recent higher-order perturbative QCD calculations available. References [8,9] and references therein provide the steps used to calculate the $gg \rightarrow H$ cross section. The MSTW 2008 next-to-next-to-leading order (NNLO) PDF set [10] is used to predict the $gg \rightarrow H$ production cross section. The calculations of associated production and VBF cross sections are described in Refs. [11–13]. The branching fractions for the Higgs boson decays are obtained from HDECAY [14]. After all selections, the total number of expected Higgs boson events is approximately 30 per experiment for $m_H = 165$ GeV, which corresponds to the region of greatest sensitivity.

Both experiments determine the multijet background by studying control samples, which are then extrapolated into the signal regions. For CDF, backgrounds from SM WW , WZ , ZZ , $W\gamma$, Drell-Yan, and $t\bar{t}$ production are generated using the PYTHIA, MC@NLO [15], and the UB/EB [16] programs. Backgrounds from W + jets processes, including (for CDF) semileptonic diboson events, single top, and semileptonic $t\bar{t}$ events, are modeled using W + jets data events and a measurement of the rate at which jets are misidentified as leptons. For D0, these backgrounds are generated using PYTHIA, ALPGEN [17], and COMPHEP [18], with PYTHIA providing parton showering and hadronization for all generators.

The diboson backgrounds are normalized using next-to-leading order (NLO) calculations from MCFM [19]. The $t\bar{t}$ and single top production cross sections are taken from Refs. [20,21] and Ref. [22], respectively. NNLO calculations [23] are used by both the CDF and D0 Collaborations for the Drell-Yan background, and by D0 for the inclusive

W/Z processes. Other backgrounds are normalized to experimental data. Both collaborations use NLO simulations and data control samples to improve the modeling of differential distributions. Systematic uncertainties on the rates of the expected signal and the expected backgrounds, as well as on the shapes of the final discriminants, are included. More details are given in Refs. [3,4].

We perform the combination twice, using Bayesian and modified frequentist approaches in turn. We check the consistency of the results to verify that the final result does not depend on the details of the statistical formulation. Both combinations test signal mass hypotheses in 5 GeV steps for values of m_H between 130 and 200 GeV, i.e., the mass range in which $H \rightarrow W^+W^-$ is the dominant decay mode. These two combinations give similar results (the limits agree within 5%). Both methods use the distributions of the final discriminants, and not just the total event counts passing selection requirements.

Both statistical procedures form, for a given Higgs boson mass, a combined likelihood [including priors on systematic uncertainties, $\pi(\vec{\theta})$] based on the product of likelihoods for the individual channels, each of which in turn is a product over histogram bins:

$$\mathcal{L}(R, \vec{s}, \vec{b}|\vec{n}, \vec{\theta})\pi(\vec{\theta}) = \prod_{i=1}^{N_C} \prod_{j=1}^{N_{\text{bins}}} \mu_{ij}^{n_{ij}} \frac{e^{-\mu_{ij}}}{n_{ij}!} \prod_{k=1}^{n_{\text{sys}}} e^{-\theta_k^2/2} \quad (1)$$

where the first product is over the number of channels (N_C), and the second product is over histogram bins containing n_{ij} events, binned in ranges of the final neural-network discriminants used for the individual analyses. The predictions for the bin contents are $\mu_{ij} = R \times s_{ij}(\vec{\theta}) + b_{ij}(\vec{\theta})$ for channel i and histogram bin j , where s_{ij} and b_{ij} represent the expected SM signal and background in the bin, and R is a scaling factor applied to the signal. By scaling all signal contributions by the same factor we make the assumption that the relative contributions of the different processes at each m_H are as given by the SM. Systematic uncertainties are parameterized by the dependence of s_{ij} and b_{ij} on $\vec{\theta}$. Each of the n_{sys} components of $\vec{\theta}$, θ_k , corresponds to a single independent source of systematic uncertainty scaled by its standard deviation, and each parameter may have an impact on several sources of signal and background in different channels, thus accounting for correlations.

In the Bayesian method we assume a uniform prior in the signal yield. Gaussian priors are assumed for the θ_k , truncated so that no prediction is negative. The posterior density function is then integrated over the θ_k (including correlations) and a 95% C.L. upper limit on R , R_{lim} , satisfies

$$\frac{\int_0^{R_{\text{lim}}} \int \mathcal{L}(R, \vec{s}, \vec{b}|\vec{n}, \vec{\theta})\pi(\vec{\theta})d\vec{\theta}dR}{\int_0^\infty \int \mathcal{L}(R, \vec{s}, \vec{b}|\vec{n}, \vec{\theta})\pi(\vec{\theta})d\vec{\theta}dR} = 0.95. \quad (2)$$

The modified frequentist technique uses the statistical variable CL_s , defined in Ref. [24], to test hypotheses which correspond to the presence or absence of Higgs boson signals. The test statistic is the log-likelihood ratio $LLR = -2 \ln \frac{p(\text{data}|s+b)}{p(\text{data}|b)}$, where $p(\text{data}|s+b)$ and $p(\text{data}|b)$ are the probabilities that the data are drawn from the $s+b$ and b -only hypotheses, respectively. The probabilities p are computed using the best-fit values of the parameters θ_k , separately for each of the two hypotheses [25]. The use of these fits extends the procedure used at LEP [24], improving the sensitivity when the expected signals are small and the uncertainties on the backgrounds are large. Two p -values are computed: $CL_b = p(LLR \geq LLR_{\text{obs}}|b)$ and $CL_{s+b} = p(LLR \geq LLR_{\text{obs}}|s+b)$, where LLR_{obs} is the value of the test statistic computed for the data. The ratio $CL_s = CL_{s+b}/CL_b$ is used to define confidence intervals and is chosen to reduce the potential for excluding a signal for which there is insufficient sensitivity. If $CL_s < 0.05$ for a particular choice of $s+b$, that hypothesis is excluded at the 95% C.L. Systematic uncertainties are included by fluctuating the predictions for s_{ij} and b_{ij} when generating the pseudoexperiments used to compute CL_{s+b} and CL_b .

Though many sources of systematic uncertainty differ between the experiments and analyses, all appropriate correlations are taken into account in the combined limits. The dominant systematic uncertainties arise from cross section calculations for the signals and the backgrounds; these are correlated between the experiments. Variations of the parton distribution functions and the renormalization and factorization scales give rise to uncertainties of 11% for the gluon-gluon fusion process [26], 5% for associated WH and ZH production [11,12], and 10% for VBF [11,13]. CDF, which uses analyses separated in jet multiplicity bins, applies a channel (jet bin) dependent uncertainty of 7% to 70% and a gluon PDF uncertainty of 8% on $gg \rightarrow H$, following the treatment discussed in Ref. [26]. For the gluon-gluon fusion signal process, we study the effects on the acceptance and the kinematics of scale variations, gluon PDF variations, and the differences between next-to-next-to-leading log calculations and the generators used for the central predictions, using the FEHIP and HNNLO programs [8,27]. We find additional uncertainties of 5% to 10%. The primary background, W^+W^- production, has a cross section uncertainty of 7% and a similar study of the acceptance and kinematics finds additional uncertainties of approximately 1% to 5%. The systematic uncertainties on WZ , ZZ , $t\bar{t}$, single top production, and Drell-Yan production range from 7% to 10%. The uncertainties on the multijet background are uncorrelated between the experiments and range from 2% to 15%. The uncertainties on the yields of $W + \text{jets}$ and $W\gamma(+\text{jets})$ range from 7% to 30%, but these have small effects on the results because the rates of these backgrounds are low. Because the methods of estimating the $W + \text{jets}$ and $W\gamma(+\text{jets})$ backgrounds differ between CDF and D0, we assume there is no correlation

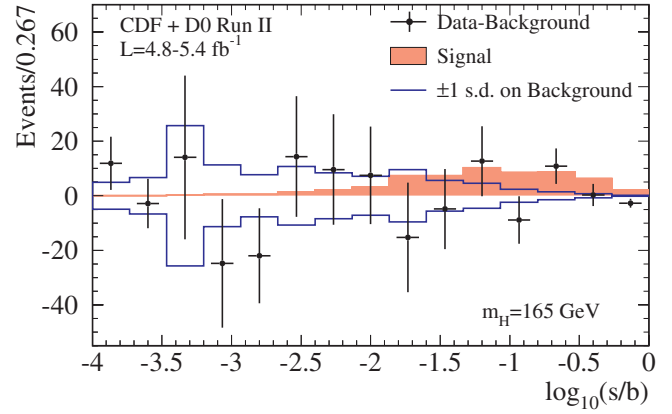


FIG. 1 (color online). Background-subtracted data distributions for the discriminant histograms, summed for bins with similar s/b , for the $m_H = 165$ GeV combined search. The background has been fit to the data under the b -only hypothesis, and the uncertainty on the background is the post-fit systematic uncertainty. The signal, which is normalized to the SM expectation, is shown with a filled histogram. The uncertainties shown on the background-subtracted data points are the square roots of the post-fit background predictions in each bin, representing the expected statistical uncertainty on the data.

between these rates. The uncertainties on the lepton identification and the trigger efficiencies are uncorrelated between the experiments and range from 2% to 6%. The uncertainty on the integrated luminosity of 6% is taken to be correlated between the signal and the Monte Carlo-based background predictions, and partially correlated between the experiments, via the 4% uncertainty on the inelastic $p\bar{p}$ cross section [28]. Additional details related to the treatment of systematic uncertainties are given in

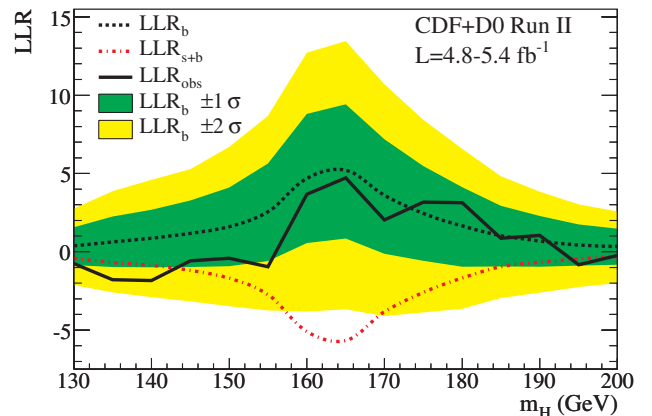


FIG. 2 (color online). Distributions of LLR as functions of the Higgs boson mass. We display the median values of the LLR distribution for the b -only hypothesis (LLR_b), the $s+b$ hypothesis (LLR_{s+b}), and for the data (LLR_{obs}). The shaded bands indicate the 68% and 95% probability regions in which the LLR is expected to fluctuate, in the absence of signal.

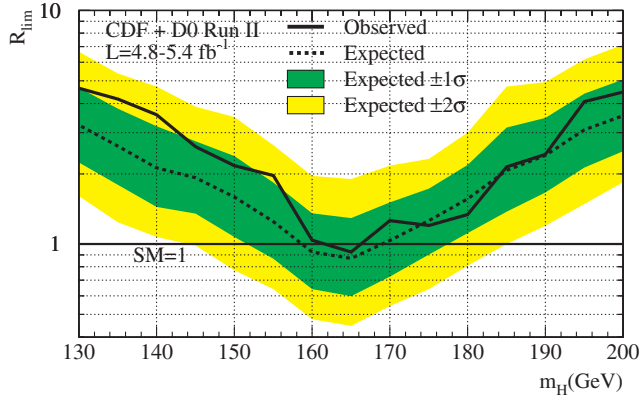


FIG. 3 (color online). Observed and expected (median, for the background-only hypothesis) 95% C.L. upper limits on SM Higgs boson production. The shaded bands indicate the 68% and 95% probability regions in which R_{lim} is expected to fluctuate, in the absence of signal. The limits displayed in this figure are obtained with the Bayesian calculation.

Refs. [3,4]. As bin by bin uncertainties arising from the statistical uncertainty in the Monte Carlo (and in some cases data) samples were shown to affect the observed and expected limits by less than 1%, they are neglected.

To better visualize the impact of the data events, we combine the histograms of the final discriminants, adding the contents of bins with similar s/b ratios, so as not to dilute the impact of highly-sensitive bins with those with less discriminating power. Figure 1 shows the signal expectation and the data with the background subtracted, as a function of the s/b ratio of the collected bins. The background model has been fit to the data, and the uncertainties on the background are those after the systematic uncertainties have been constrained by the fit. No excess of candidate events in the highest s/b bins relative to the background expectation is observed.

Before extracting the combined limits, we study the LLR distributions for the $s+b$ and b -only hypotheses, shown in Fig. 2 as functions of m_H . The separation between the median LLR_b and LLR_{s+b} divided by the widths is a measure of the discriminating power of the search. The value of LLR_{obs} relative to the expected $s+b$ and b -only distributions indicates whether the observed data are more consistent with the presence of signal, or not. No signifi-

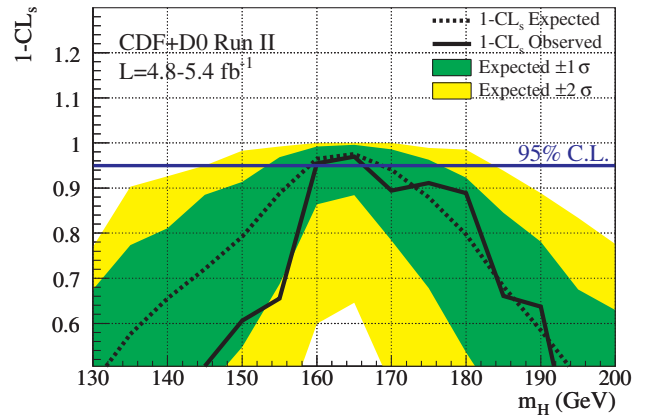


FIG. 4 (color online). Distribution of $1-\text{CL}_s$ as a function of the Higgs boson mass obtained with the CL_s method. The shaded bands indicate the 68% and 95% probability regions in which the LLR is expected to fluctuate, in the absence of signal.

cant excess of data above the background expectation is seen for any value of m_H . Because the same data events are used to construct the observed LLR at each m_H tested, the LLR values are highly correlated from one m_H to the next. This also applies to Figs. 3 and 4 described below.

We extract limits on SM Higgs boson production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV in the $m_H = 130\text{--}200$ GeV mass range. We present our results in terms of R_{lim} , the ratio of the limits obtained to the rate predicted by the SM, as a function of the Higgs boson mass. We assume the production fractions for WH , ZH , $gg \rightarrow H$, and VBF, and the Higgs boson decay branching fractions, are those predicted by the SM. A value of R_{lim} less than or equal to one indicates a Higgs boson mass that is excluded at the 95% C.L.

The ratios of the expected and observed limits to the SM cross section are shown in Fig. 3 as a function of m_H . The observed and median expected ratios are listed in Table I, with observed (expected) values for the Bayesian method of 1.04 (0.92) at $m_H = 160$ GeV, 0.93 (0.87) at $m_H = 165$ GeV, and 1.26 (1.04) at $m_H = 170$ GeV. We use piecewise linear interpolations to display the combination results in Figs. 2–4, and to quote the observed and expected excluded mass ranges. We exclude the SM Higgs boson in the mass range 162 to 166 GeV. The Bayesian calculation,

TABLE I. Ratios, R_{lim} , of the median expected and observed 95% C.L. limits to the SM cross section for the combination of CDF and D0 analyses as a function of the Higgs boson mass in GeV, obtained with the Bayesian (upper) and the CL_s (lower) methods.

Bayesian	130	135	140	145	150	155	160	165	170	175	180	185	190	195	200
Expected	3.24	2.63	2.12	1.92	1.59	1.25	0.92	0.87	1.04	1.26	1.56	2.07	2.40	3.09	3.55
Observed	4.65	4.18	3.58	2.61	2.17	1.96	1.04	0.93	1.26	1.20	1.34	2.14	2.42	4.07	4.47
CL_s	130	135	140	145	150	155	160	165	170	175	180	185	190	195	200
Expected	3.26	2.52	2.18	1.87	1.53	1.24	0.89	0.84	1.06	1.28	1.56	2.07	2.46	3.17	3.62
Observed	4.49	4.06	3.45	2.49	2.12	1.84	0.98	0.89	1.21	1.18	1.31	2.15	2.36	4.10	4.35

chosen *a priori*, was used for this exclusion. The corresponding expected exclusion, from 159 to 169 GeV, encompasses the observed exclusion. The CL_s calculation yields similar results, as shown in Fig. 4. The $1-CL_s$ distribution, which can be directly interpreted as the level of exclusion of our search, is displayed as a function of the Higgs boson mass. For instance, our expected limit shows that in the absence of signal the median $1-CL_s$ value with which we expect to exclude a SM Higgs boson of mass 165 GeV is 97%.

In summary, we present the first combined Tevatron search for the SM Higgs boson using the $H \rightarrow W^+W^-$ decay mode. No significant excess of candidates is found above the background expectation for $130 < m_H < 200$ GeV. We exclude the mass range from 162 to 166 GeV at the 95% C.L. This is the first direct constraint on the mass of the Higgs boson beyond that obtained at LEP.

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^aDeceased.

^bVisitor from University of Massachusetts Amherst, Amherst, Massachusetts 01003, USA.

^cVisitor from Universiteit Antwerpen, B-2610 Antwerp, Belgium.

^dVisitor from University of Bristol, Bristol BS8 1TL, United Kingdom.

^eVisitor from Chinese Academy of Sciences, Beijing 100864, China.

^fVisitor from Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy.

^gVisitor from University of California Irvine, Irvine, CA 92697, USA.

^hVisitor from University of California Santa Cruz, Santa Cruz, CA 95064, USA.

ⁱVisitor from Cornell University, Ithaca, NY 14853, USA.

^jVisitor from University of Cyprus, Nicosia CY-1678, Cyprus.

^kVisitor from University College Dublin, Dublin 4, Ireland.

^lVisitor from University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom.

^mVisitor from University of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017.

ⁿVisitor from Kinki University, Higashi-Osaka City, Japan 577-8502.

^oVisitor from Universidad Iberoamericana, Mexico D.F., Mexico.

^pVisitor from University of Iowa, Iowa City, IA 52242, USA.

^qVisitor from Iowa State University, Ames, IA 50011, USA.

^rVisitor from Kansas State University, Manhattan, KS 66506, USA.

^sVisitor from Queen Mary, University of London, London, E1 4NS, United Kingdom.

^tVisitor from University of Manchester, Manchester M13 9PL, United Kingdom.

^uVisitor from Muons, Inc., Batavia, IL 60510, USA.

^vVisitor from Nagasaki Institute of Applied Science, Nagasaki, Japan.

^wVisitor from University of Notre Dame, Notre Dame, IN 46556, USA.

^xVisitor from Obninsk State University, Obninsk, Russia.

^yVisitor from University de Oviedo, E-33007 Oviedo, Spain.

^zVisitor from Texas Tech University, Lubbock, TX 79609, USA.

^{aa}Visitor from IFIC (CSIC-Universitat de Valencia), 56071 Valencia, Spain.

^{bb}Visitor from Universidad Tecnica Federico Santa Maria, 110v Valparaiso, Chile.

^{cc}Visitor from University of Virginia, Charlottesville, VA 22906, USA.

^{dd}Visitor from Bergische Universität Wuppertal, 42097 Wuppertal, Germany.

^{ee}Visitor from Yarmouk University, Irbid 211-63, Jordan.

^{ff}On leave from J. Stefan Institute, Ljubljana, Slovenia.

^{gg}Visitor from Augustana College, Sioux Falls, SD, USA.

^{hh}Visitor from The University of Liverpool, Liverpool, United Kingdom.

ⁱⁱVisitor from SLAC, Menlo Park, CA, USA.

^{jj}Visitor from ICREA/IFAE, Barcelona, Spain.

^{kk}Visitor from Centro de Investigacion en Computacion-IPN, Mexico City, Mexico.

^{ll}Visitor from ECFM, Universidad Autonoma de Sinaloa, Culiacán, Mexico.

^{mmm}Visitor from Universität Bern, Bern, Switzerland.

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